High-Efficiency Asymmetric Transmission of Circularly Polarized THz waves using a Dielectric Herringbone Metasurface

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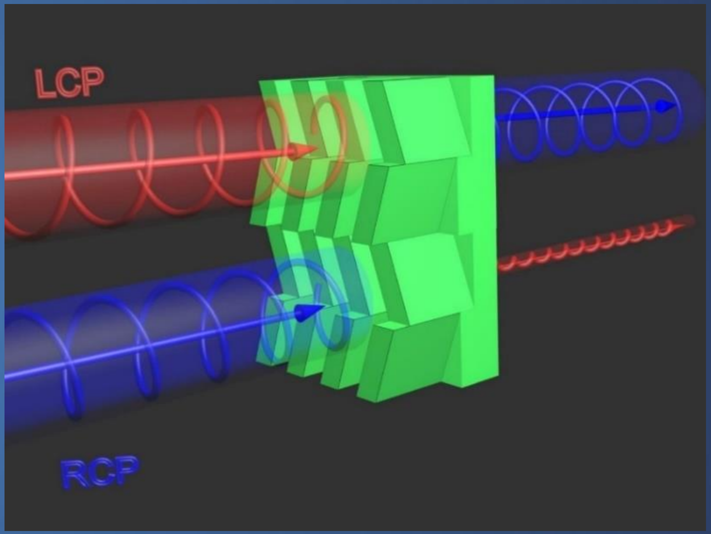

M. Kenney *et al.*, Adv. Mater. **28**, 9567 (2016)

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NANOP 2017
PUTTING NANOPHOTONICS TO WORK
NANOPHOTONICS AND MICRO/NANO OPTICS
INTERNATIONAL CONFERENCE / SEPT 13-15, 2017
BARCELONA

Overview

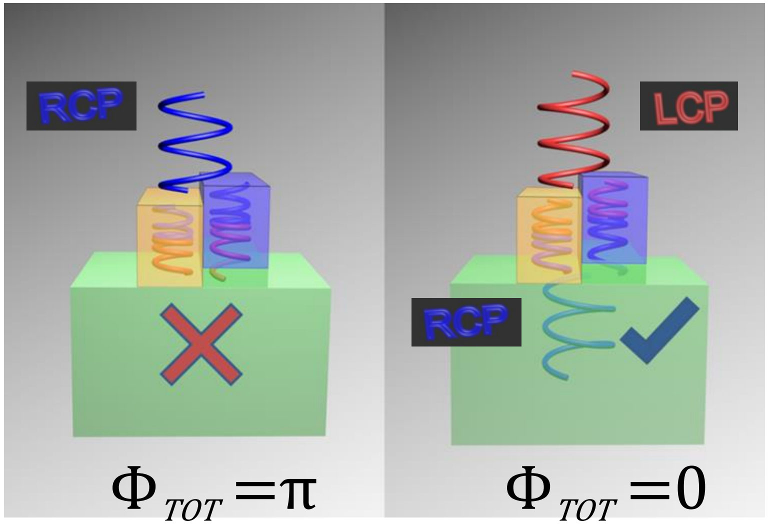
- Primary Objective
- Motivation & Background
- Design
- Simulation & Analytical results
- Fabrication
- Experimental Results
- Conclusion and Future Prospects

Primary Objective

- Achieve ***Asymmetric Transmission*** (or ***Conversion Circular Dichroism***) in THz regime using **dielectric** metasurface.

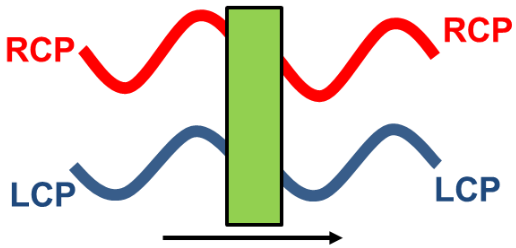
- Based on combination of ***Geometric phase*** (Pancharatnam-Berry Phase) and ***Dynamic phase***.

→ Interference between the two phase mechanisms.



Motivation & Background

What is Asymmetric Transmission/ Conversion Circular Dichroism?



Normal, isotropic homogenous media
Negligible cross-conversion

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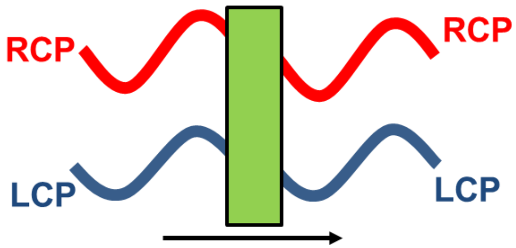

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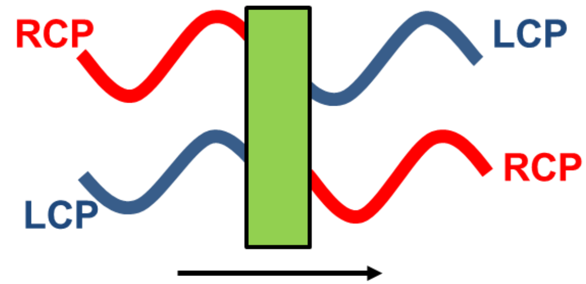

Birefringent media, e.g. half-wave plate
Complete polarisation conversion, large amount of cross-conversion in equal amounts

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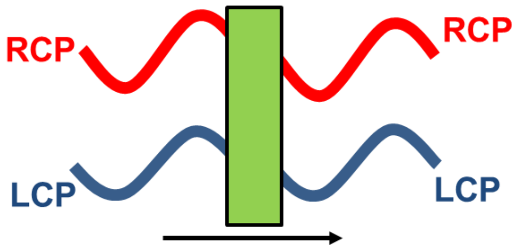

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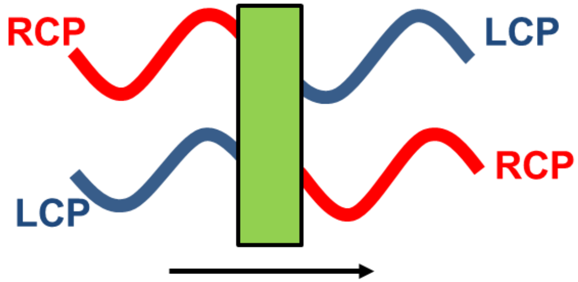

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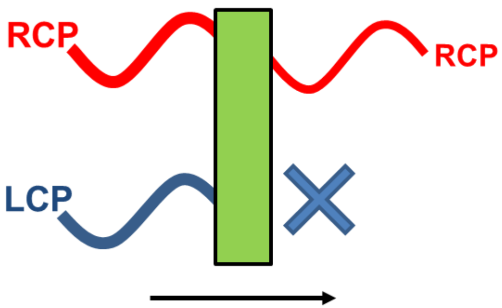

3D chiral media, e.g. helix/spiral
Circular Dichroism, one handedness absorbed more than the other, some cross-conversion

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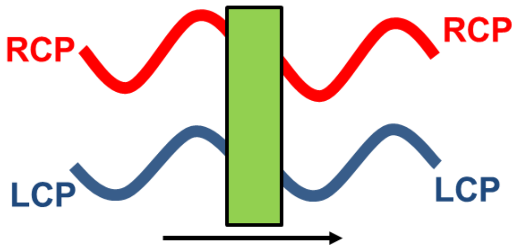

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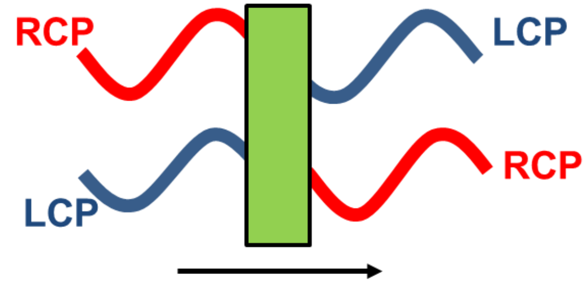

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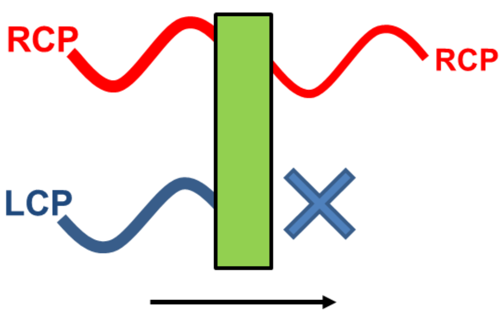

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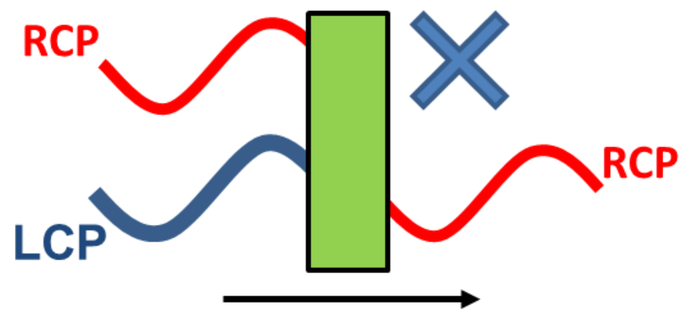
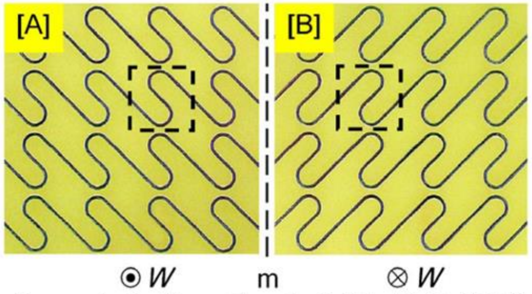


2D chiral media, e.g. meander/asymmetric split ring
Conversion Circular Dichroism (asymmetric transmission), fully flips one handedness, prevents the other (reflection)

Motivation & Background

- Previous designs use metal structures → lossy!
- For single layer designs, small conversion efficiency
  → intrinsic mechanism only allows less than 25% conversion.
- Multilayer designs have better efficiency (53%), but still lossy (37% loss) and involve complex designs/fabrication [Pfeiffer *et al.*]
- Need to develop a 'trivial' method of achieving this phenomenon…



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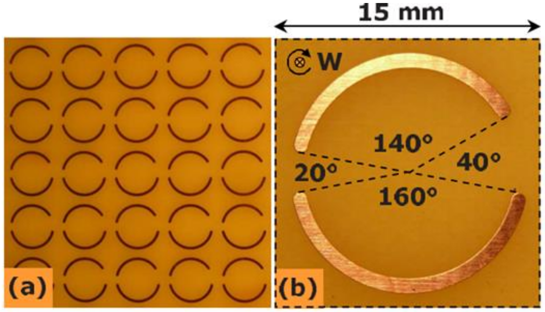

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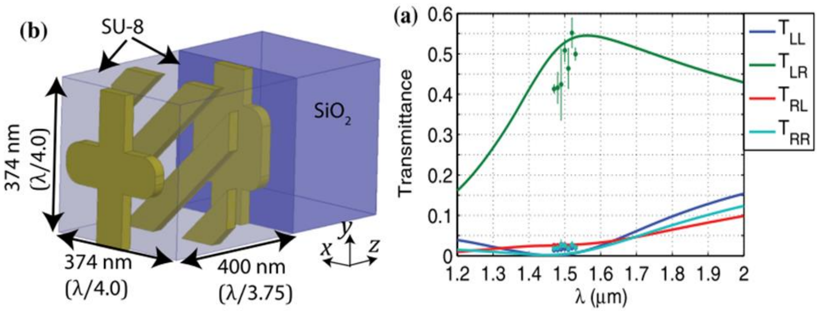

Pfeiffer *et al.*, *Phys. Rev. Lett.* **113**, 023902 (2014)

Design

Step 1: Flip the handedness!

Half wave-plate → using Subwavelength Gratings (SWG's)

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Step 2: Introduce phase disparity between handedness' → **Geometric Phase**

→Pancharatnam–Berry Phase! $\varphi_{Geometric} = \pm 2\theta$ ('+' RCP/'−' LCP)

Phase difference between two structures. e.g. $\boxed{\theta=\pi/4, \text{so, } \varphi_{Geometric} = \pm\pi/2.}$

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Step 3: Introduce a <u>fixed</u> dynamic phase between the two structures

$\varphi_{Dynamic} = \Delta n_{Si-Air}(2\pi d/\lambda)$ → need to get d, the elevation height

$$\boxed{\varphi_{Dynamic} = +\pi/2}$$

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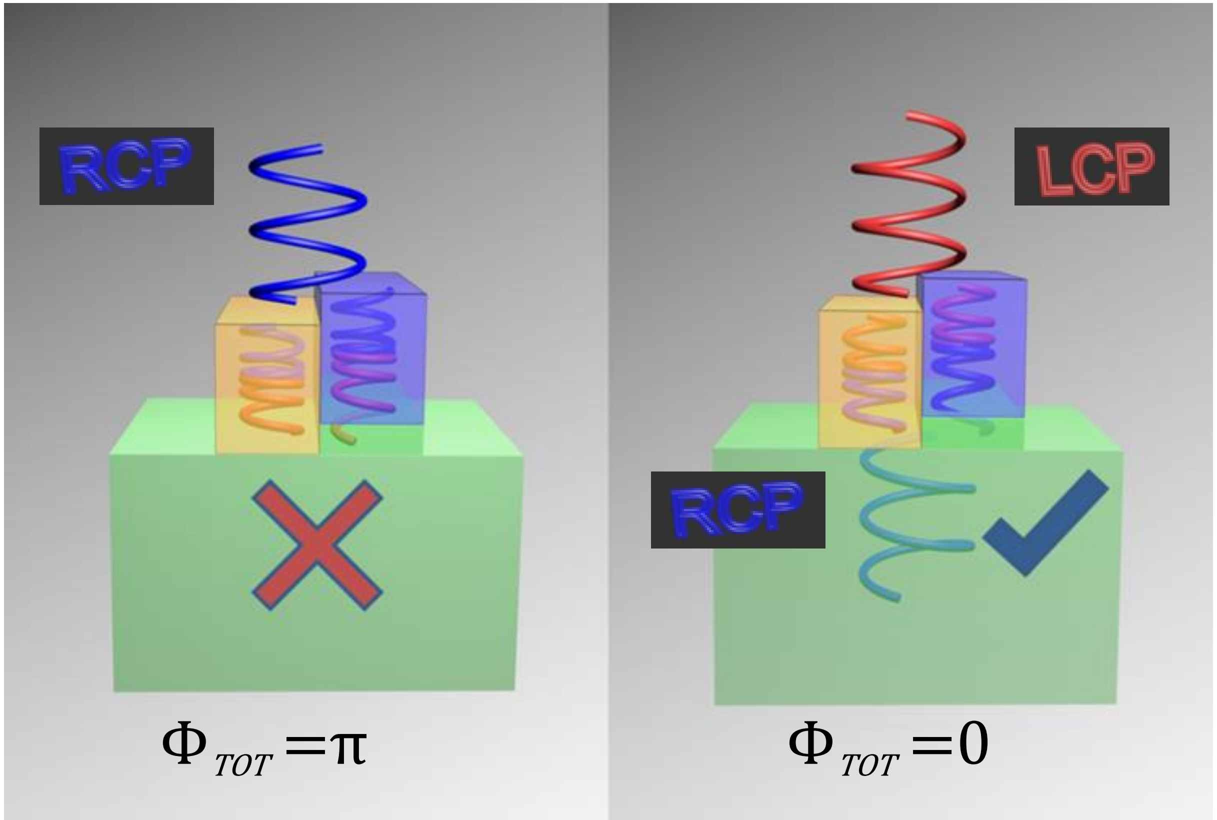


Design

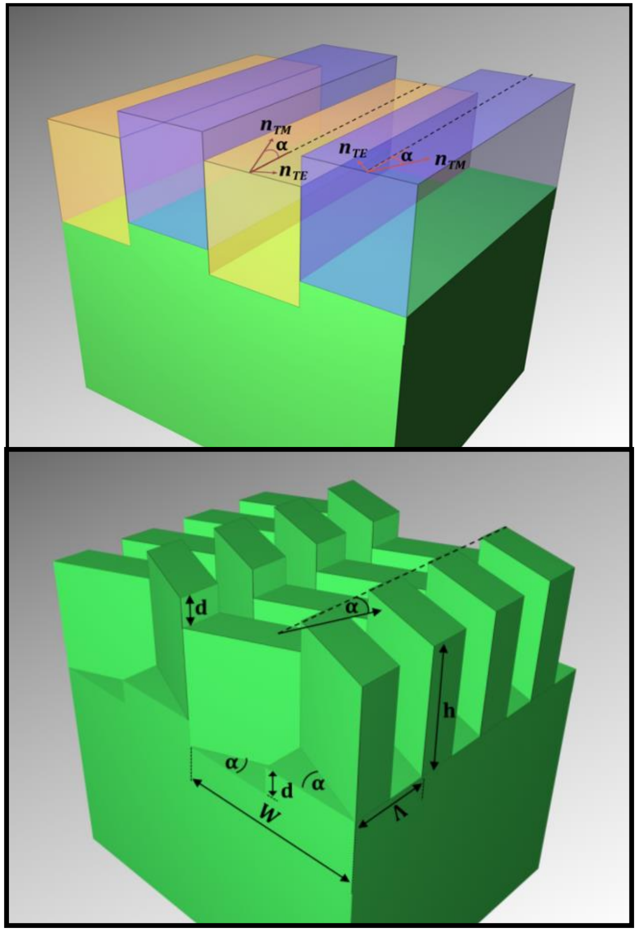
- Designed structure is analogous to using birefringent crystals

- Use Subwavelength gratings for half-wave plate:
  → Period condition is: $\boxed{\Lambda \leq \lambda / n_{\mathrm{II}}}$

  Λ is period, λ is free-space wavelength, n_{II} is refractive index of substrate

  → Want to perform at 1 THz, use silicon (10kΩ): λ=300 µm, n_{II} = 3.418 → $\Lambda \leq$ 87.7 µm

  <u>Choose Λ = 86 µm</u>



Design

- Need to calculate depth and duty-cycle of SWG's.

Grating equation: $$\boxed{\Delta\Phi_{TE-TM}(\lambda) = \left(\frac{2\pi h}{\lambda}\right)\Delta n_{form}(\lambda)}$$

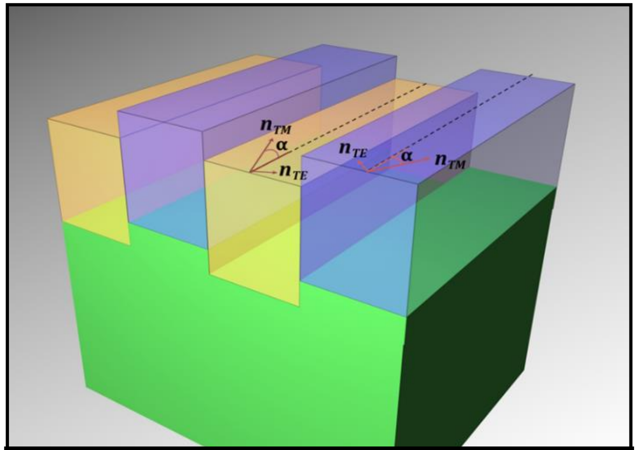
- $\Delta\Phi_{TE-TM}$ is the (wavelength-dependent) phase difference between parallel (TE) and perpendicular (TM) components of light in the grating

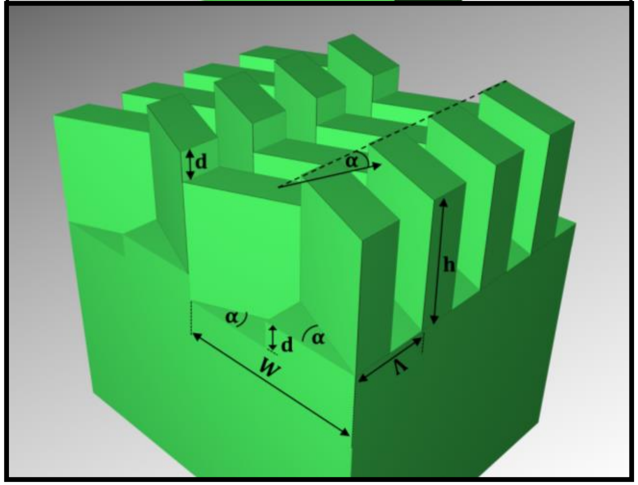
- h is the depth of the gratings

- Δn_{form} is the difference in refractive indices along the TE and TM directions of the grating, given as:

$$\boxed{\Delta n_{form} = n_{TE}(\lambda) - n_{TM}(\lambda)}$$

$$\boxed{n_{TE} = \left(F n_{\mathrm{I}}^2 + (1-F) n_{\mathrm{II}}^2\right)^{1/2}} \qquad \boxed{n_{TM} = \left(F n_{\mathrm{I}}^{-2} + (1-F) n_{\mathrm{II}}^{-2}\right)^{-1/2}}$$





- Using a duty cycle of F = 0.5, and $n_I = 1$ for air, we have:

$$n_{TE} = 2.52 \qquad n_{TM} = 1.36 \qquad \longrightarrow \qquad \Delta n_{form}(\lambda) = 1.16$$

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Design

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$$\Delta n_{form}(\lambda) = 1.16 \rightarrow \Delta\Phi_{TE-TM}(\lambda) = \left(\frac{2\pi h}{\lambda}\right)\Delta n_{form}(\lambda)$$

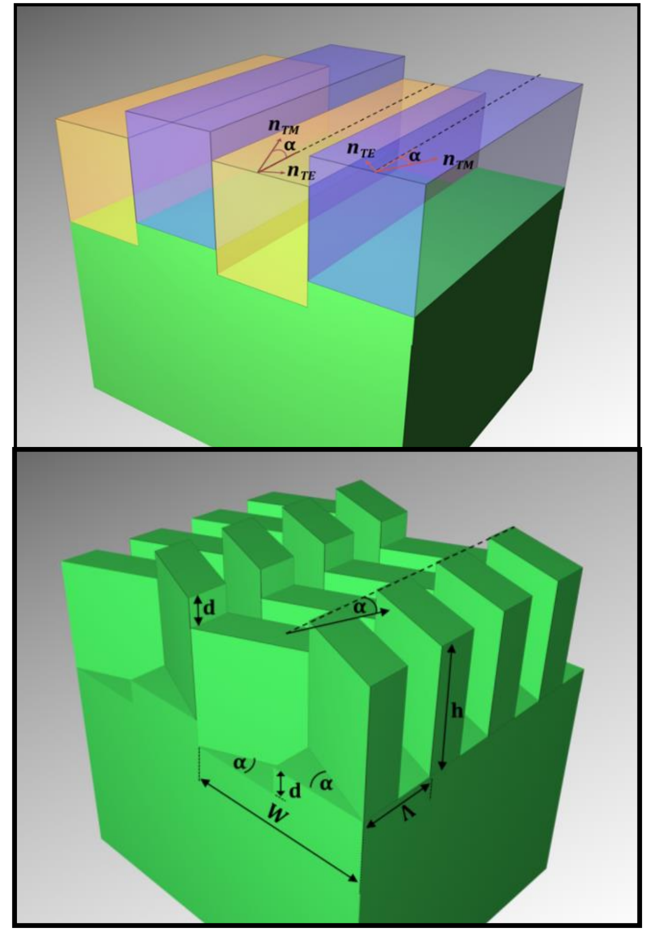
- Want Half-wave plate functionality, choose $\Delta\Phi = \pi$

Rearrange to get $\underline{h = 129\ \mu\text{m}}$

- Apply P-B phase of $\pi/2$ by setting $\alpha = 22.5°$
- Apply dynamic phase of $\pi/2$ by adding a step beneath one grating, need to calculate step height d

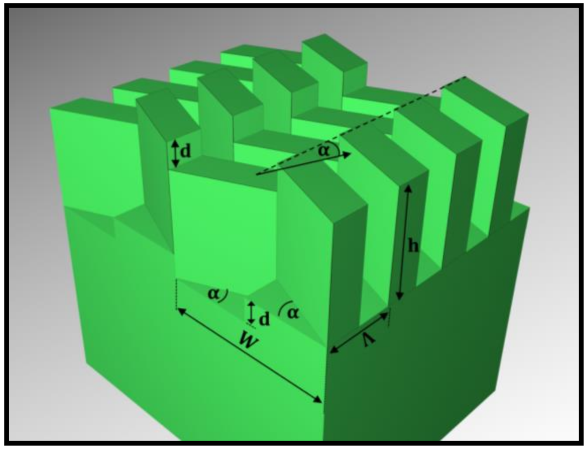
Use equation: $\boxed{\Delta\varphi_{Dyn} = \Delta n_{Si-Air}(2\pi d/\lambda)}$

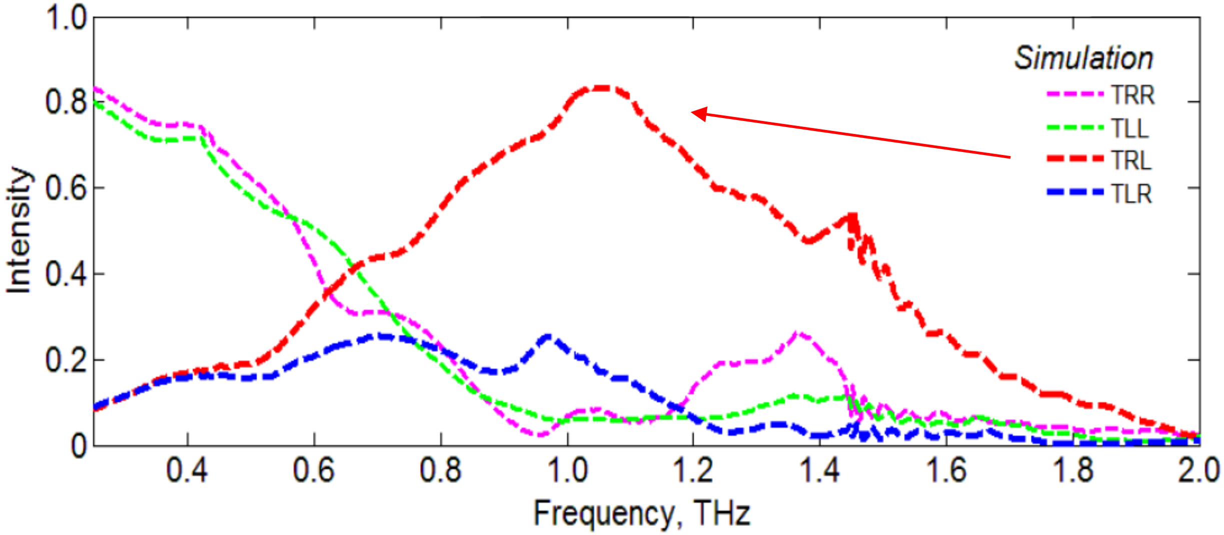
Simply get $\underline{d = 31\ \mu m}$



Simulation

- Simulate using CST Microwave studio





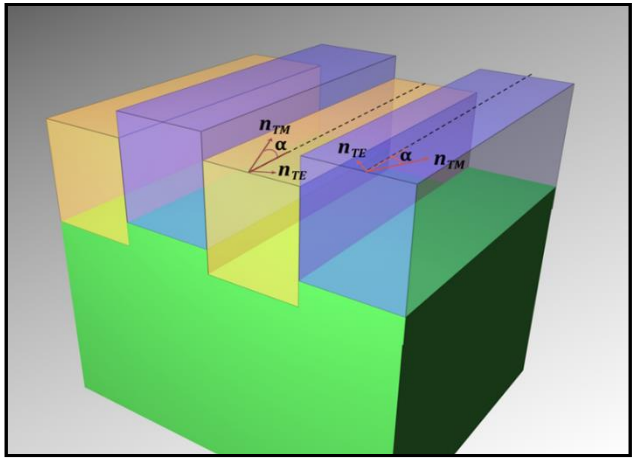
- Very high cross polarisation, $T_{RL} \approx 85\%$ @ 1.05THz
- T_{LR} is low (15% @ 1.05THz) as required
- Unconverted (co-pol.) values are low, <10% @ 1.05THz

Analytical

- Use analytical model based on Fresnel's equations for a three-layer system.

$$t_i = \frac{t_{12_i} t_{23_i} e^{-i\phi}}{1 + r_{12_i} r_{23_i} e^{-2i\phi}}$$

$$\phi_i = \frac{2\pi d}{\lambda} n_{2i}$$



$$t_{12_i} = 2n_1/(n_1 + n_{2i})$$

$$t_{23_i} = 2n_{2i}/(n_{2_i} + n_3)$$

$$r_{12_i} = (n_1 - n_{2i})/(n_1 + n_{2i})$$

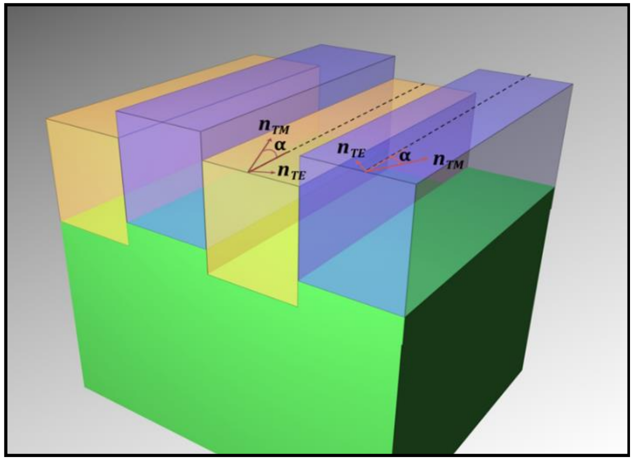
$$r_{23_i} = (n_{2i} - n_3)/(n_{2_i} + n_3)$$

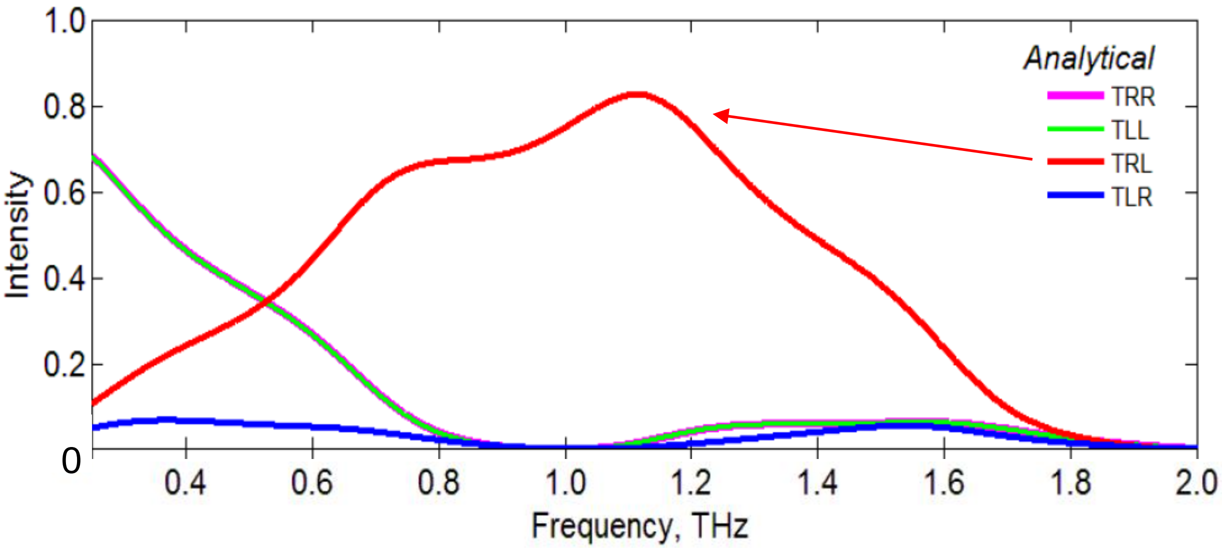
- Use this equation to describe yellow SWG without phases

- Introduce P-B and dynamic phases to 2nd blue SWG, sum the two transmittances together:

$$T = n_3 \left| \frac{1}{2} \left(t + t \cdot e^{i\phi_{Dyn}} \cdot e^{i\phi_{Geom}} \right) \right|^2$$

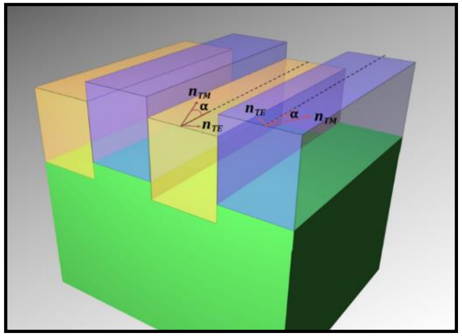
Analytical

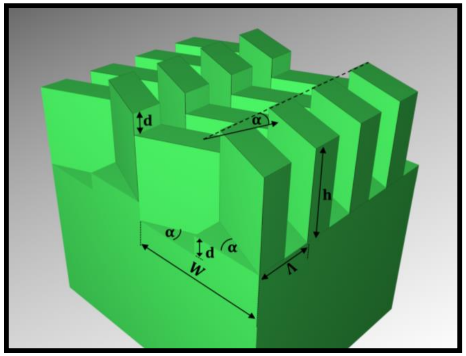


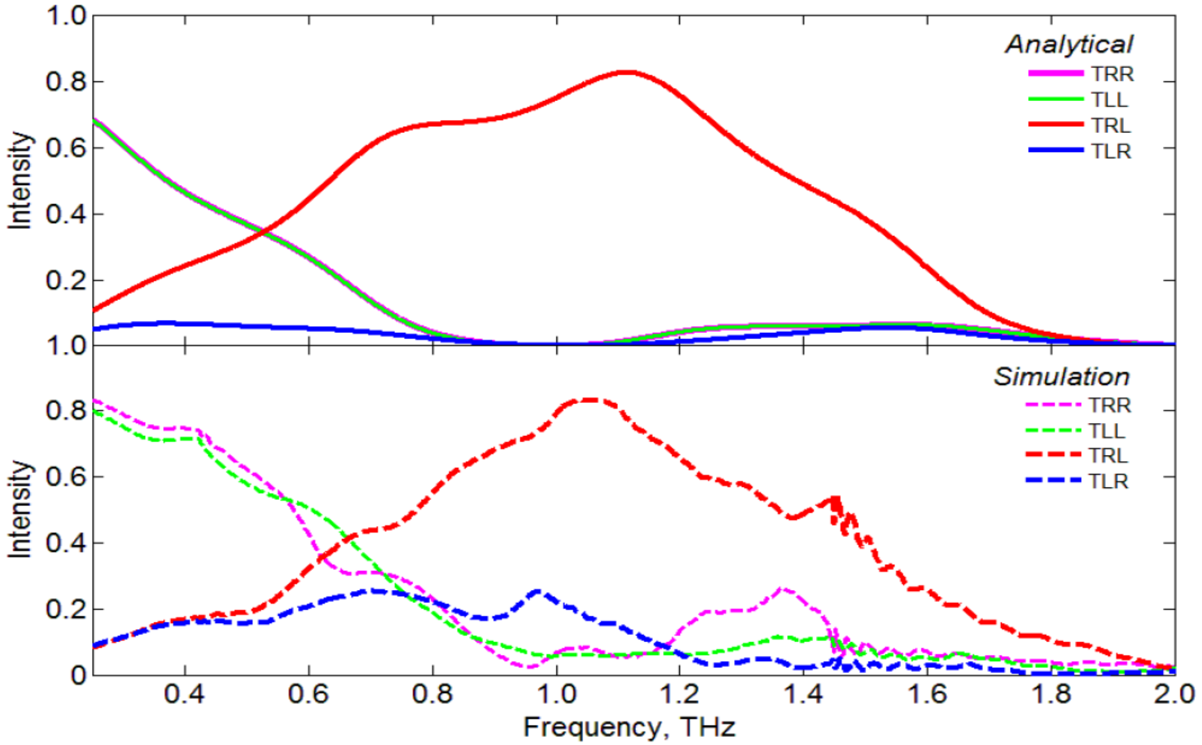


- Similar results to simulation
- Very high cross polarisation, T_{RL} ≈ 85% @ 1.1THz
- T_{LR} is low (~1% @ 1.1THz)
- Unconverted (co-pol.) values are low, <1% @ 1.1THz

Analytical & Simulation







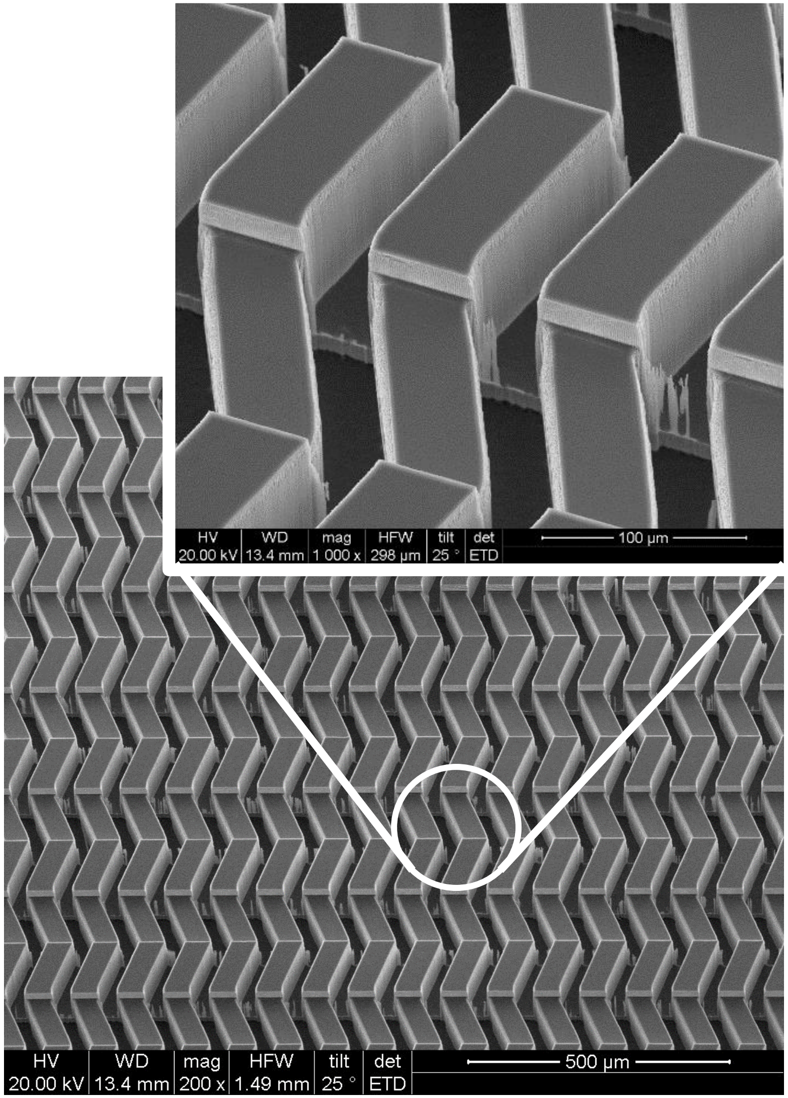
- Slight mismatch in central frequency and design of 1 THz

→ SWG's are based on 1st order effective medium theory, period actually ~80μm
→ Fabry- Pérot effects between layers, differs from single-pass theory
→ SWG's & step not dispersionless, operation changes for wavelength

Fabrication

- Standard photolithography and Deep Reactive Ion Etching used to fabricate silicon wafer

- First, stripes of 31 µm step are fabricated by etching
- Then, zig-zags overlaid, and etched down 129 µm.



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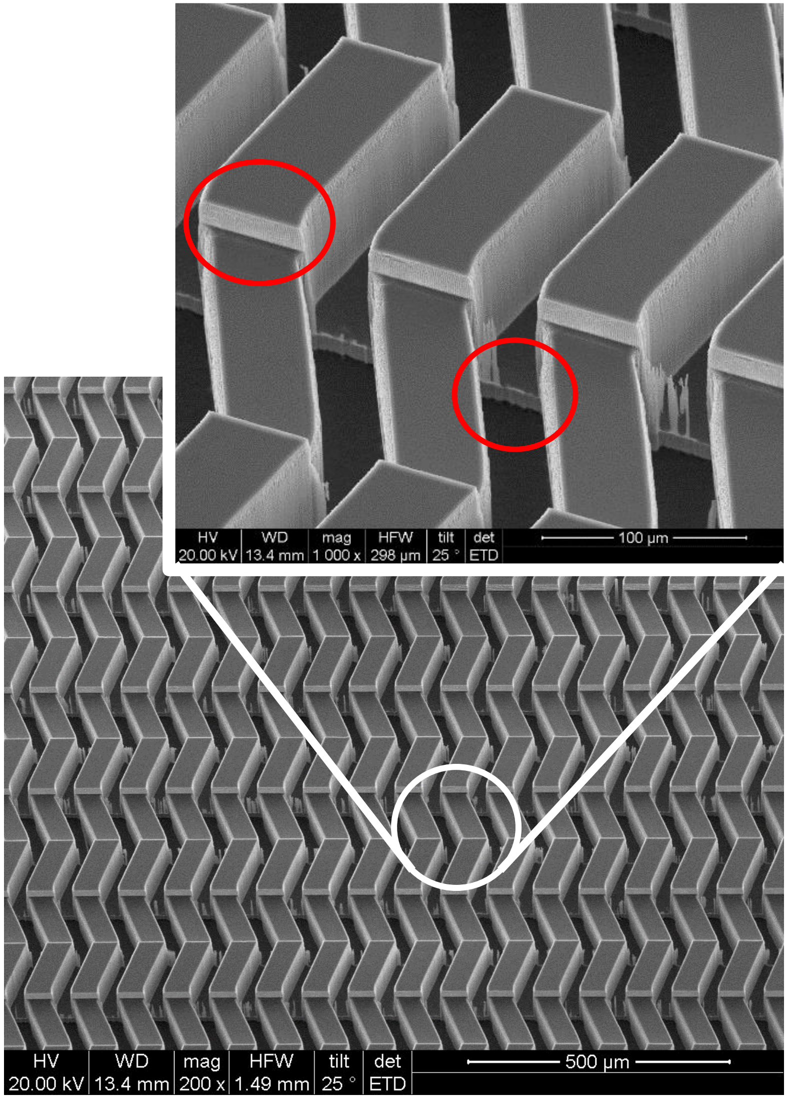
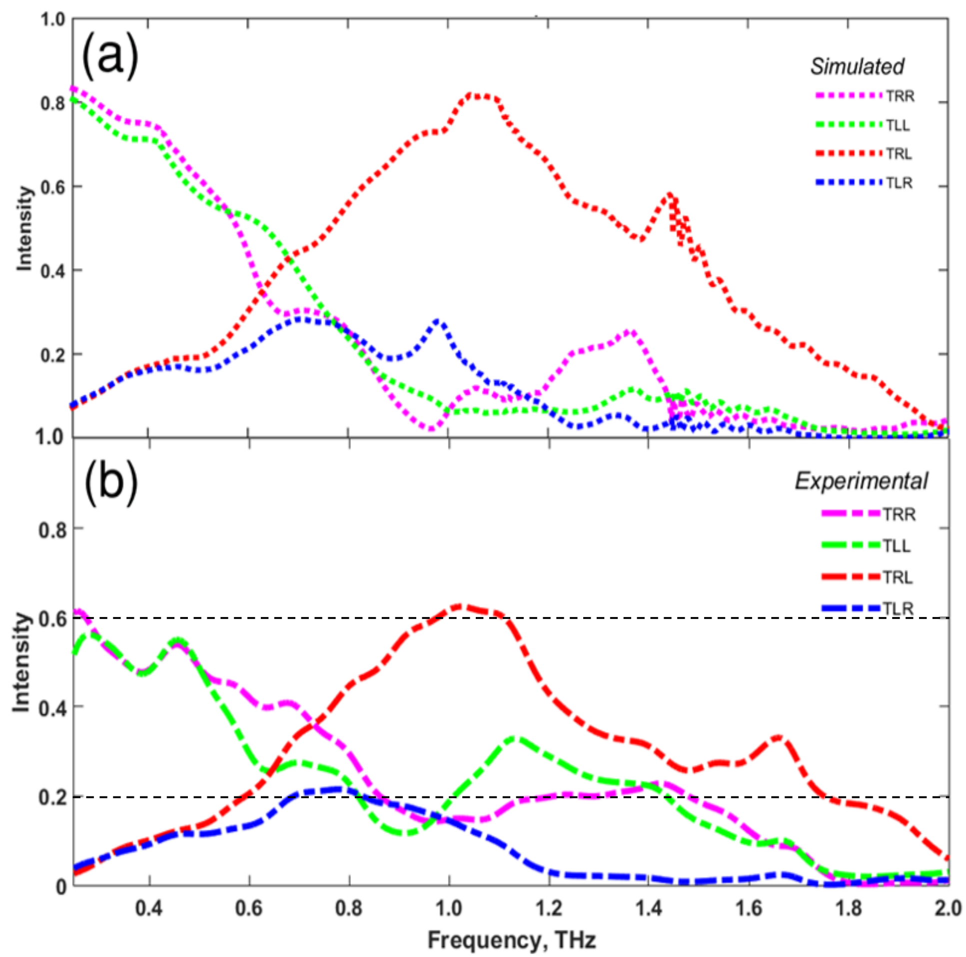
- Slight difference between bottom step and top step (red circles)
  → Re-simulate to reflect this



Experimental Results

- Simulation not too different to previous 'desired' parameters
- THz-TDS (Time Domain Spectroscopy) used to obtain experimental data.
  → Linear polarisation, post-processing to convert to circular basis
- Experimental result impressive
  → $T_{RL} \approx 63\%$ @ 1.025THz
  → $T_{LR} \approx 13\%$
  → Extinction ratio approx. 5:1
- Un-converted polarisations are <20%
- Difference between exp. & sim. due to fabrication errors, step mismatch, and side-wall slope, material losses

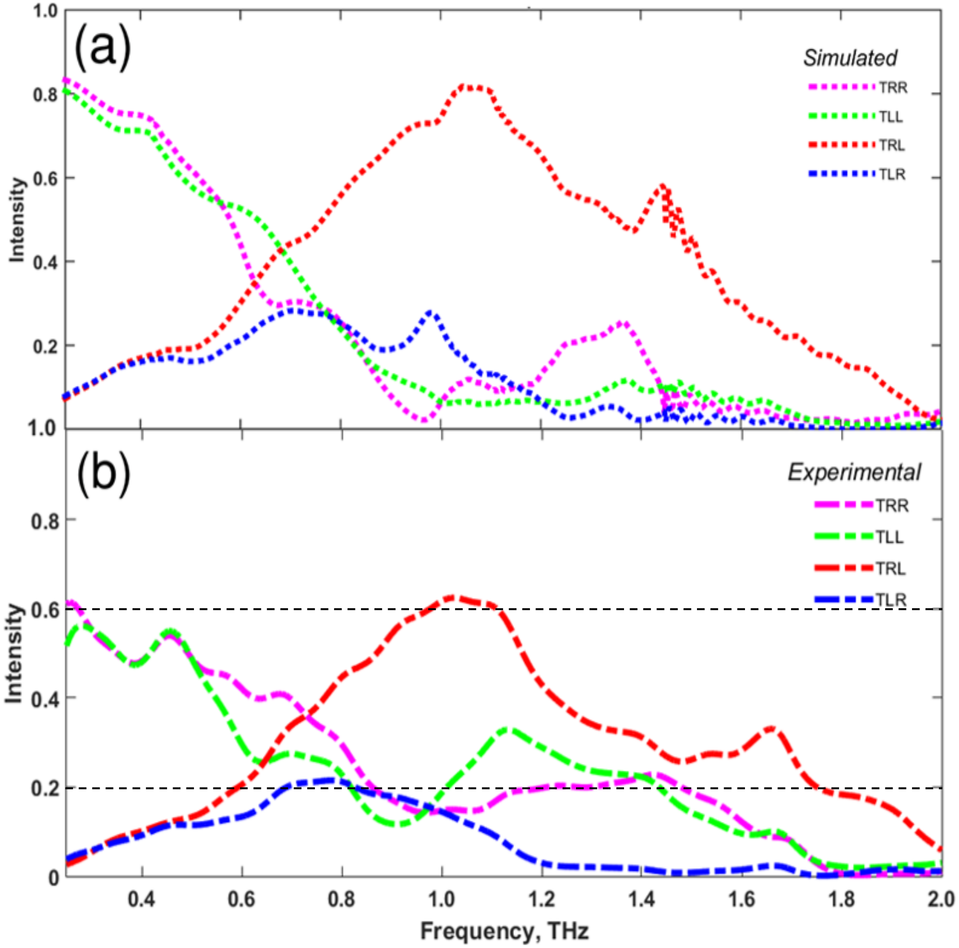


Experimental Results

- Very broadband, FWHM of 0.72 THz at central frequency of 1.025 THz → $\Delta f/f$ = 70%

- Total energy, T_R and T_L:
  → T_R = 28%
  → T_L = 84%
- R = 1 – T (ignore absorption)
  → Implies that R_R is 72%

- The device can be used to distinguish between L and R to a high efficiency



Conclusion

- Achieved Asymmetric Transmission/Conversion Circular Dichroism using dielectric metasurface, not metallic
- Straight-forward approach, rather than trial-and-error optimization of impedances between layers etc…
- Obtained highest recorded AT of 63% (to our knowledge) in the THz regime (possibly all regimes)
- Very broadband, $\Delta f/f$ = 70%, and extinction ratio of 5:1 between T_{RL} and T_{LR}
- TL = 84% and RR = 72%, can use device to distinguish handedness of incident light to high efficiency

Future Prospects

- Potential for use in other frequency regimes

- Dielectric nanobricks, e.g. TiO_2 for visible light, act as half-wave plates
  → incorporate extra phase step beneath opposing element to induce handedness dependence

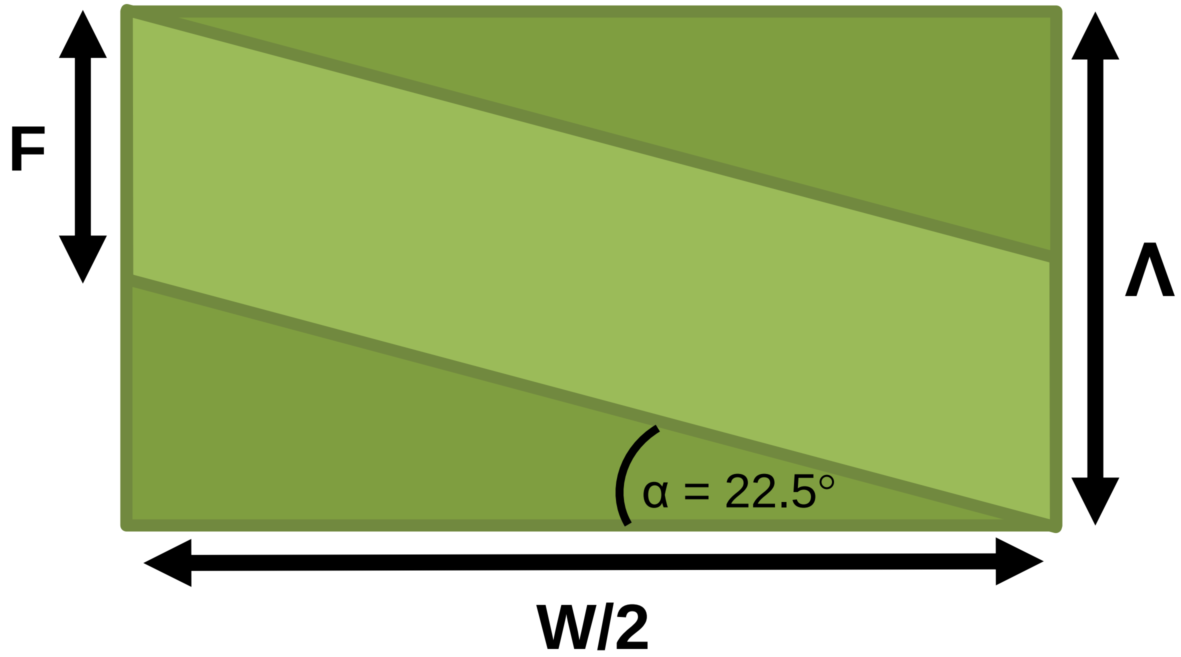
- Could have holograms which only operate for one handedness, have holographic image in different quadrants in +Z and –Z axis

- Linear-to-circular lenses, using P-B phase with only one foci, not two


Thank you

Subwavelength Gratings

- Duty cycle, F = 0.5
- Λ = 86 μm, not quite equal to actual period of gratings
  → actual period ~80μm
- W = 208 μm, due to geometry



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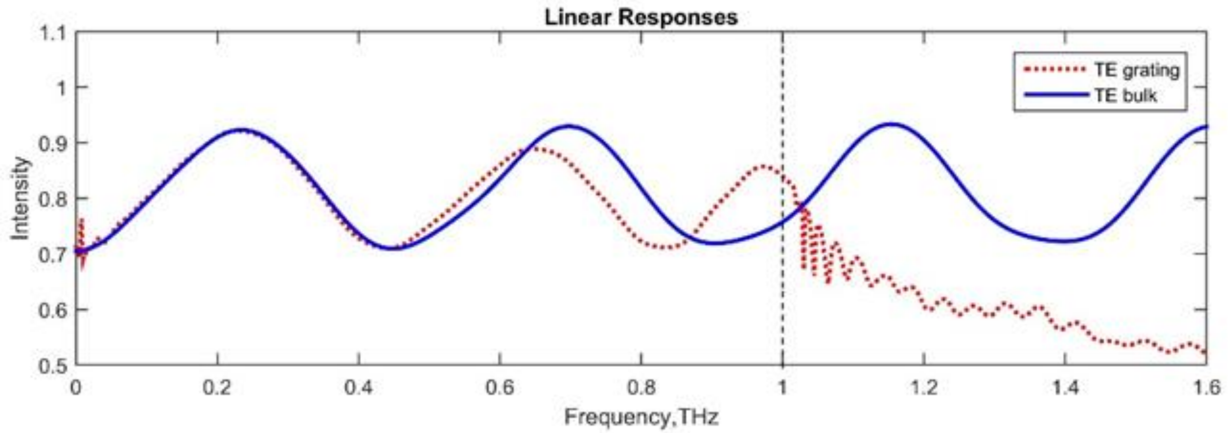
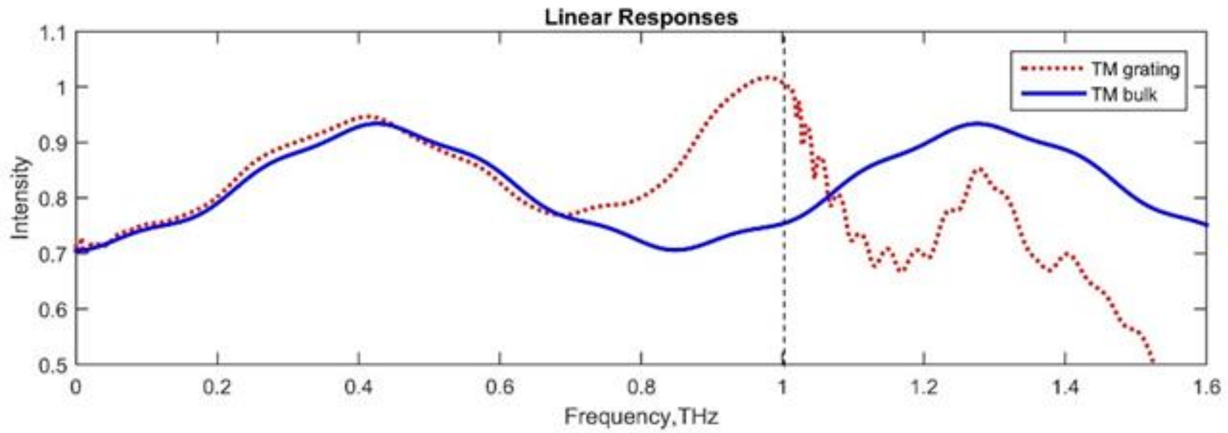
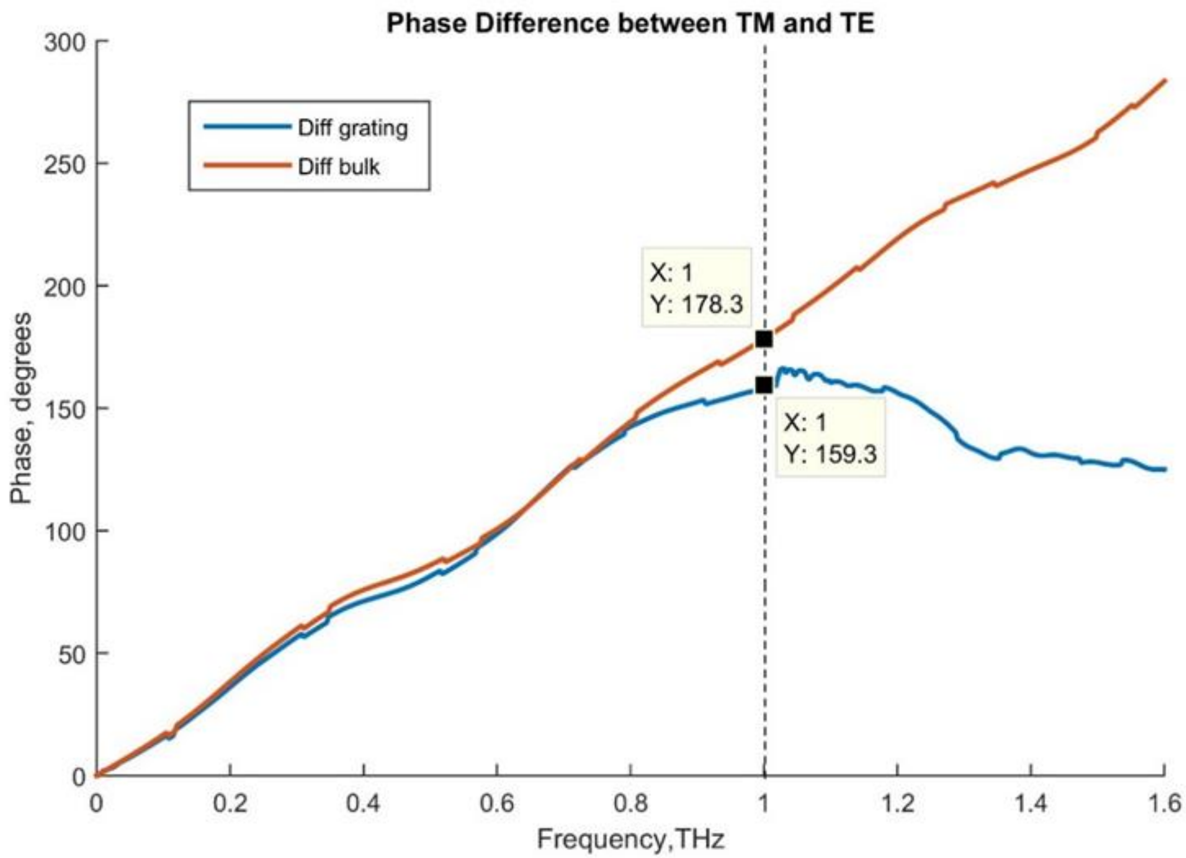




Subwavelength Gratings

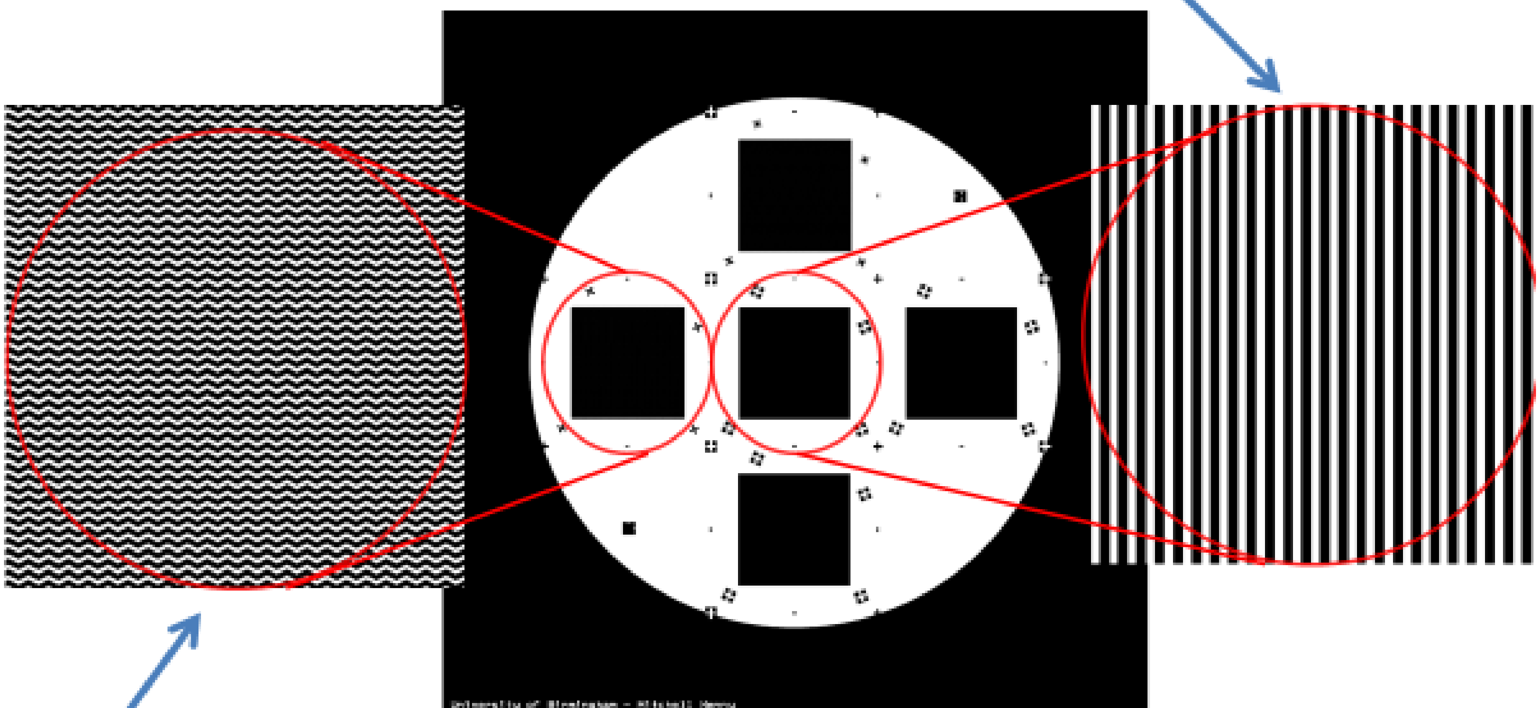
- Grating not too different to 'desired' bulk parameters
  → approx. π phase difference → Half-wave plate



Fabrication

Photomask

1st Pattern to etch - STRIPES



2nd Pattern to etch - ZIGZAGS

Fabrication

Procedure